Superconducting gravimeters in seismology

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A Global network of more than 20 Superconducting Gravimeters (SGs) (Figure 1) has been collecting data since July 1997 under the auspices of the Global Geodynamics Project, (GGP) (http://www.eas.slu.edu/GGP/ggphome). The GGP was organized to establish a common data archive with standardized data formatting and raw data processing protocols to provide scientists, including those without expertise in superconducting gravity data collection and processing, access to this unique global data set. These data have contributed to numerous and diversified disciplines in the Earth science, such as investigations involving tidal gravity, ocean tidal and atmospheric loading, inner and outer core oscillations, polar motion, continental water mass observations, and volcanology (For a complete review of the scientific applications of superconducting gravimeter data and the GGP, the reader is referred to *Crossley et al*., 1999).

The unique feature of a superconducting gravimeter is the broad spectrum of gravity changes (Figure 2) that can be observed. Periods ranging from seismic free oscillations, including the translational modes of the inner core (Slichter triplet whose detection is still controversial), to periods larger than a year, for example the Chandler wobble.

The Chandler Wobble is the name given to the movement of the Earth's pole by 0.7 arc-seconds over a period of about 435 days. For more information, visit the web site of the International Earth Rotation and Reference Systems Service (IERS) at www.iers.org. The Chandler Wobble can be modelled by 'simply' fitting a harmonic series of sines or cosines to the past record of deflections, and then using this empirical model to make limited forecasts into the future. The cause of this wobble is believed to reside in the natural resonances in the body of the

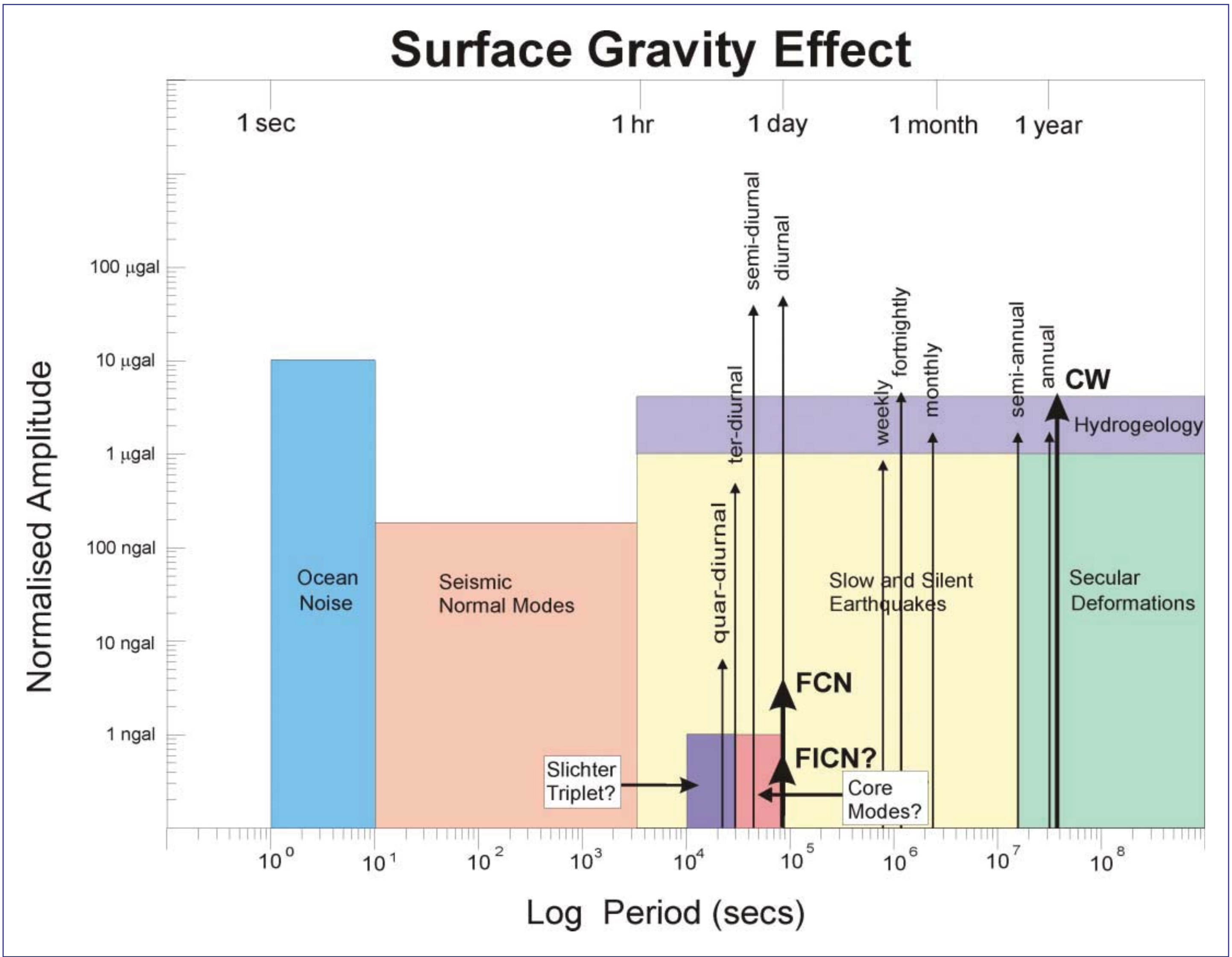

Figure 1: *Surface gravity spectrum showing the wide spectral range (from 1 second to several year periods) observable with superconducting gravimeters (from Crossley and Hinderer, 1995)*

spinning earth due to the detailed distribution of mass in its surface, interior, oceans and atmosphere. This system has a '14-month' harmonic which can be excited through a complex pattern of forcings by the moon, sun and sudden crustal rearrangements (earthquakes). There are many distinct periodic excitations by the sun and moon and their changing distances and tidal forcings, and these result in distinct monthly, yearly and multi-year periodicities in the polar wander. The Chandler Wobble may be a natural harmonic resonance that is also stimulated by these other constant lunar-solar forcings at the natural resonance frequency of the solid earth. A workshop «Forcing of polar motion in the Chandler frequency band: A contribution to understanding interannual climate variations» organized by the European Center for Geodynamics and Seismology will be held on April 21-23, 2004 in Luxembourg (more information at www.ecgs.lu)

In the field of seismology, the recent generation of the superconducting gravimeters promises to achieve even lower instrumental noise as compared to sensors currently deployed in the Global Seismographic Network (GSN) and used in studies of the Earth's free oscillations (*Widmer-Shnidrig*, 2003)

The fundamental component of a SG (*Warburton and Brinton*, 1995, Goodkind, 1999) consists of a hollow superconducting sphere that levitates in a persistent magnetic field. In a way, the SG is a spring gravimeter in which the mechanical spring is replaced by the magnetic levitation of a superconducting sphere above superconducting coils. An incremental change in gravity induces a vertical displacement of the sphere. A feedback voltage is applied to keep the sphere at a 'zero' position. This feedback voltage is proportional to the gravity change. Thus, the SG provides *relative* gravity measurements.

Due to the size of the SG, its power requirements, and the need to refill the instrument at least annually with helium, the most common mode of operation is continuously at a fixed location (Figure 3). While these requirements make remote observations difficult, successful sites such as Syowa, Antarctica and Ny Alesund, Norway (on Spitsbergen Island almost 80 degrees north of the equator) are testament to the fact that many of the requirements can be overcome.

Being a relative meter, the SG needs to be calibrated in order to convert observed variations in voltage into actual gravity changes. This is achieved by operating an *absolute* gravimeter side-by-side with the SG. This method of calibration allows for a precision in the calibration factor better than 0.1%.

Seismic Normal Modes

The spectral range observable with an SG is broad, ranging from the seismic frequency band (free oscillations) to periods longer than one year (Chandler wobble). In this short note, we discuss an example of an application in the seismic frequency band (periods shorter than one hour), in particular on the observation of seismic normal modes.

Usually this seismic band is investigated using broadband seismometers such as the STS-1. Relative gravimeters, such as the LaCoste-Romberg spring gravimeters, are also able to retrieve these modes as shown by *Zürn et al*. (1991). Numerous studies indicate that a SG can also be an excellent long-period seismograph (see, *Van camp*, 1999 and *Widmer-Shnidrig*, 2003).

It has been shown that the seismic and relative gravity instruments operating at the same quiet site have similar performance. The signal to noise ratio of the seismic modes is almost identical.

To detect the Earth's normal modes as discrete peaks in the spectra of earthquakes recordings, the earthquake generating the signals should have a magnitude which exceeds a minimum moment magnitude of $M_W \approx 6.5$ and the

Figure 3: *The last Compact Tidal SGs, manufactured by GWR Instruments (San Diego) during its set-up by the manufacturer (R. Warburton) in Walferdange (Luxembourg). The sensor uses a Nb superconducting test mass which is levitated in a magnetic field created by superconducting coils. The extremely low noise and low drift are primarily due to the operation of the components at liquid He temperatures regulated to a few micro-Kelvin inside a vacuum can. A special refrigeration unit allows the instrument to be run indefinitely with only one filling of liquid He.*

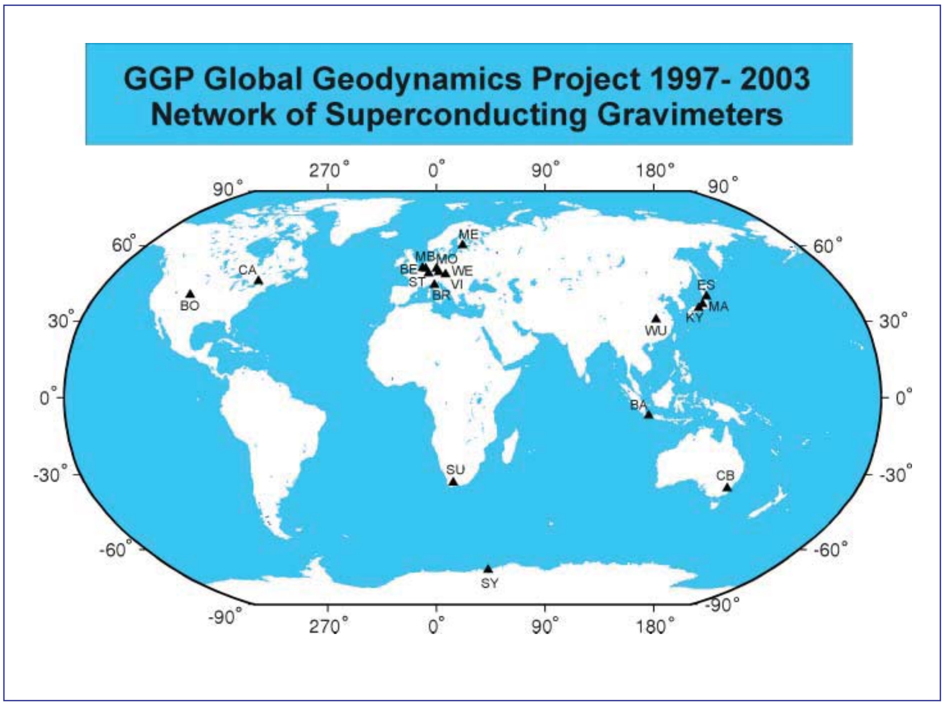

Figure 2: *The GGP network showing currently recording stations.*

minimum length of the time series required for the subsequent Fourier analysis should be longer than 3 hours. A tradeoff has to be found between the frequencies resolution and the length of the time series. As the modes attenuate, at some point increasing the length of the time series will only add noise to the analysis.

To illustrate this point, the spectrum of the data from the Peru earthquake of 23-June, 2001 (M_W=8.3) observed by SG-C021 operating in Membach Belgium is displayed in Figure 4. The eigenfrequencies are well retrieved and can be easily identified after correcting the data for the atmospheric pressure effect. The OT2 and OT3 modes are not always present as in the example. The absence of the modes is due to the fact that the coupling generating them, is not always induced by earthquakes. A remarkable feature of the example is the splitting of the 0S3 mode and the emergence of the 0S2 mode which itself is also splitted.

In conclusion, superconducting gravimeters and especially the most recent generation of instruments are becoming competitive with the best spring gravimeters and seismometers. SGs have produced data with the highest signal to noise for the modes below 0.6 mHz. They also provide excellent data in the band where splitting modes are very sensitive to the 3-D density structure of the Earth's mantle and core. The final word is taken from *Widmer-Shnidrig* (2003): "To observe this splitting and constrain lateral density structure is one avenue for which SGs are uniquely suited."

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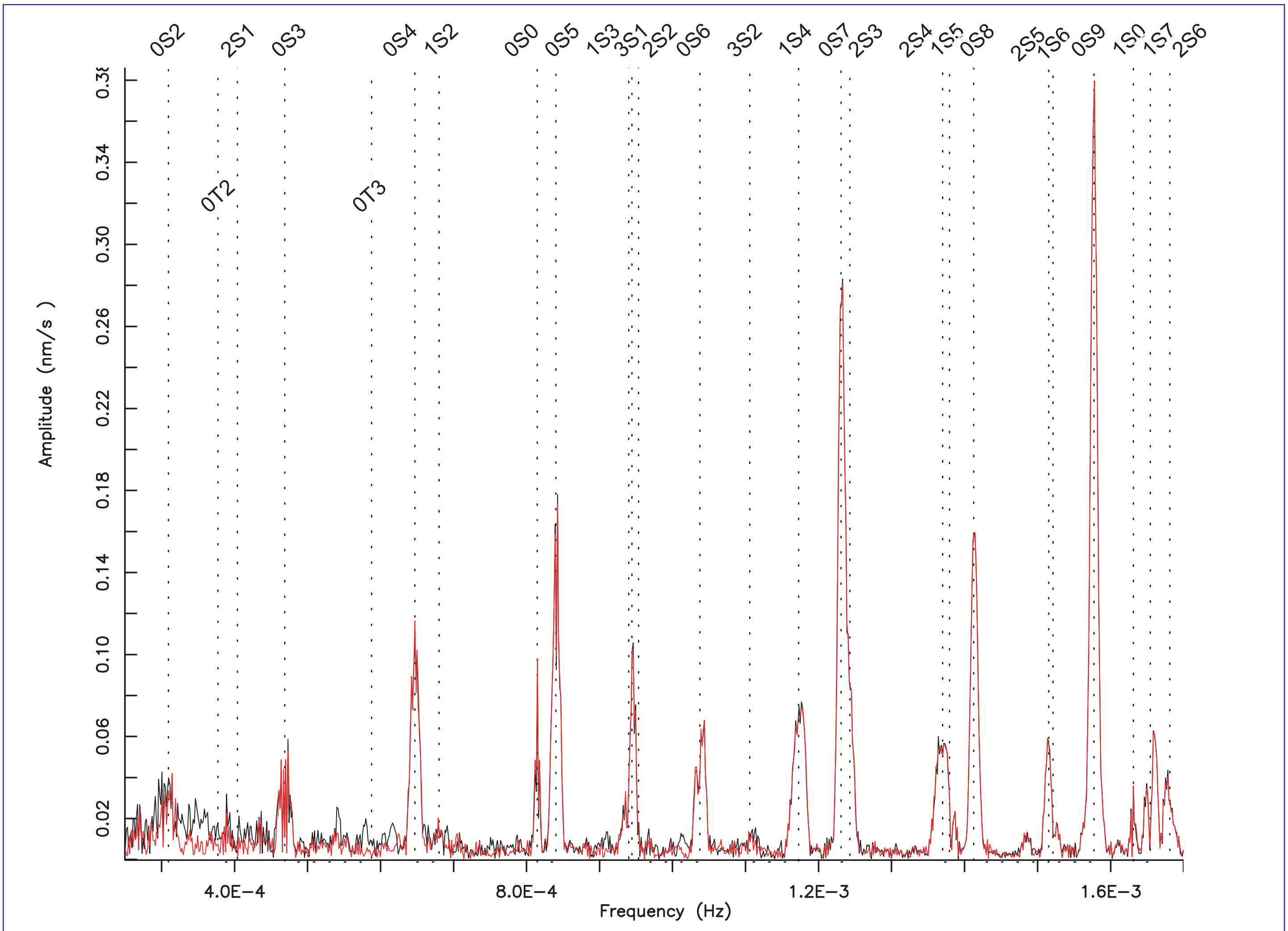

Figure 4: *Amplitude spectrum of the Peru earthquake (16.14S, 73.31W) of the 23th of June 2001 Mw=8.3 . Data from 23th of June 22h15 till 30th of June 2001 04h00 UT. Vertical dashed lines indicate theoretical eigenfrequencies (Courtesy Dr. M. Van Camp, Royal Observatory of Belgium, Seismology Section).*